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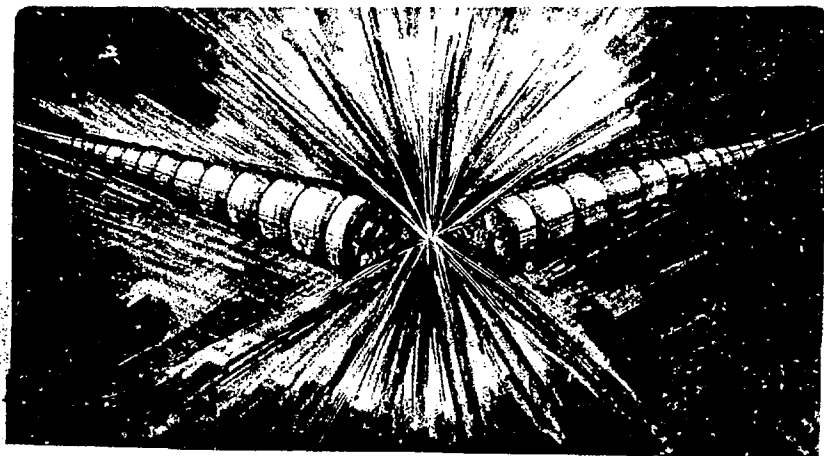
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Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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J.B. Rechen, W.S. Gilbert, and W.V. Hassenzahl
Lawrence Berkeley Laboratory
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Summary

Local correction of the sextupole error field is proposed for the dipoles of the SSC. This requirement is imposed on the design by the high field quality required both during injection at low fields and during colliding beam operation at high fields. Error fields in the main dipole windings due to superconductor magnetization and conductor misplacements add unwanted sextupole and decapole magnetic field terms. To correct the sextupole error field we have constructed sextupole coils made of a single layer of superconducting wire and have mounted them with high precision on the stainless steel bore tube. These correction coils have been operated with 1 meter long SSC model dipoles in both the self-powered and externally-powered modes. The sextupole field in the bore has been reduced by as much as a factor of 50. The level of correction depends strongly on the angular alignment of the correction coil with respect to the sextupole error field it is to correct. Results of tests, performance of the correction coils and alignment requirements for the system are presented.

Introduction

The SSC will require bending magnets whose fields contain no multipole component larger than 1 part in 10^4 of the dipole field inside a 1-cm radius. In addition to the usual field errors due to conductor misplacements, design errors and iron saturation, superconducting dipole magnets display large sextupole and decapole components due to superconductor "magnetization". This effect is due to the fields produced by persistent currents flowing on the surfaces of the superconducting filaments, which have been cycled in rising and falling magnetic fields. The effect is largest at the low fields typical of accelerator injection conditions, and is principally the sextupole and decapole components. The effect is smaller for smaller filaments. An example and comparison with theory is given in Ref. [1]. Better agreement with theory is now being obtained [2]. Figure 1 shows the sextupole component at various field levels for an LBL model SSC dipole, with and without the correction coil in operation.

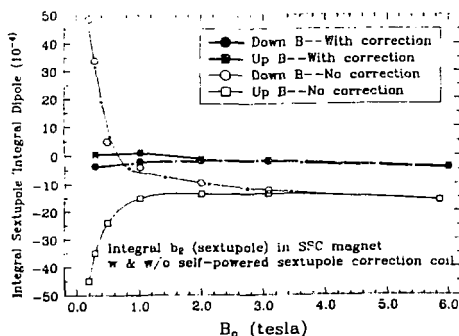


Fig. 1

Local vs. Lumped Correction

Sextupole fields are used in accelerators to control the chromaticity, or radial orbit dispersion due to energy spread in the particle beam. For optimum control, this sextupole should be generated at carefully chosen azimuthal locations around the ring, with full control of the strength and mixture of regular and skew fields, which are generated by dedicated windings. To have such control, the bending magnets should present a "pure" dipole field. Since each bending magnet will have a slightly different amount of sextupole (and also other field components), it is best to have correction coils inside these magnets, to cancel locally the unwanted components.

Correction Methods

Several laboratories have already approached this correction problem. Fermilab, in the Doubler/Tevatron, uses lumped correction elements around the ring in "spool pieces". The strength of the multipoles in each is adjusted for the average of the magnet aberrations ahead of it [3]. Brookhaven, in the proposed ISABELLE/CBA accelerators, was to use multipole windings between the magnet coil windings and the bore tube for sextupole and decapole correction in each magnet. These windings, which were externally powered, were made of superconducting wire [4]. In the experimental magnet "MOBY", CERN/Saclay used a self-powered, shorted superconducting sextupole winding inside the main coils of the magnet to cancel that component. Results were encouraging, but not pursued [5,6]. At DESY, in Hamburg, magnet prototypes for the HERA machine will have externally-powered superconducting sextupole and quadrupole windings between the main dipole windings and the bore tube. The windings are designed to correct error and magnetization fields and also to provide chromaticity correction [7,8].

Efforts at LBL

At Lawrence Berkeley Laboratory, in support of a collaboration with Brookhaven National Laboratory and Fermi National Accelerator Laboratory, we have constructed several superconducting sextupole correction coils for use with the 1-meter model dipoles that are being built to address the requirements for development of SSC bending magnets.

These sextupole correction elements consist of six coils each having 10 turns of insulated 0.60 mm copper stabilized Nb-Ti superconductor per pole, laid down on a 3.50 cm diam. stainless steel bore tube. The winding is made of one continuous piece of superconducting wire, including a dipole correction loop. A long low-resistance splice is made between the ends [9].

A shorted superconducting sextupole winding inside the main coil windings will have a current induced in it by the sextupole component of the field that is coupled to it. By Lenz's law, this current produces a field that opposes the change, thus maintaining whatever trapped field is inside the coil. Because it is superconducting and has a very low resistance shorting splice, the current will persist with a very small decay, as is required for storage ring operation.

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and covered by a heater winding, which can be used to quench the superconductivity of that portion of the coil. Two leads are attached between the section of conductor under the heater and the coil. When the heater is energized and external power is applied through these leads, the still-superconducting sextupole winding is energized, though it is partially shunted by the resistive portion of the wire under the heater.

Error Field to be Corrected

The primary goal of the LBL 1-meter model dipoles is to work out the details of the two-dimensional cross-section of the proposed LBL-BNL-FNAL candidate SSC dipole. The sextupole correction coils described here have been installed in successive iterations of this dipole and operated with each during the extensive evaluation and tests that these magnets undergo.

Since this series of magnets is being built to work out mechanical problems, and several changes have been made between each successive coil, their magnetic field quality can be termed "rich in harmonics". Some of the components of the field are large and are due to factors which will not be significant in the final refined models and full-length magnets.

Harmonic	Table I			
	D-12B(2)	High Field	D-12C(2)	High Field
b1	5.79	1.31	6.17	0.96
b2	53.49	47.15	30.61	15.71
b3	0.76	0.66	0.69	0.86
b4	2.54	1.54	3.12	3.26
b5	0.63	0.34	0.36	0.20
b6	1.12	1.28	0.40	0.17
b7	0.57	0.20	0.22	0.16
b8	0.69	0.46	0.72	0.68
b9	0.09	0.06	0.05	0.10

Field harmonic measurements on two representative magnets taken at low and high fields. Units are parts in 10^4 of the dipole field.

As can be seen Table I, the sextupole component (b2) is largest, and of a magnitude that requires considerable reduction to be acceptable.

Test Results

We have operated superconducting self-powered sextupole correction coils in five magnets to date, with varying degrees of success. Some of these tests have been reported earlier [9]. Table II shows the degree of correction attained in these tests.

Magnet	Table II					
	Low Field	Low Field	Ratio	High Field	High Field	Ratio
	Uncorr.	Corr.		Uncorr.	Corr.	
D-12A(2)	107.68	3.47	31.0	60.57	8.99	6.7
D-12B(1)	43.26	6.95	6.2	30.01	1.00	16.7
D-12B(2)	50.74	11.98	4.2	37.48	16.42	2.3
D-12B(2)*	52.08	5.44	9.6	37.11	2.06	18.0
D-12C(1)	80.94	6.58	12.3	60.54	6.17	9.8
D-12C(2)	30.61	0.81	37.8	15.71	4.36	3.6

*Realigned, retested
Units are Integral Sextupole/Integral Dipole, $\times 10^4$

The variations in the degree of correction have several causes. The early magnets had large sextupole field components, which induced high enough currents in the correction coils to cause them to quench. The interaction of these high currents and the magnetic fields also caused a deformation of the coil and the bore tube that increased the coupling of the coil to the dipole field.

Alignment of Coil and Magnet

In the succeeding magnets, which had smaller sextupole components, the angular alignment of the coil to the sextupole component of the dipole's field became the dominant limitation in the efficiency of the correction.

For a single correction coil, the angular alignment between the field pattern developed by the correction coil and the sextupole produced by the magnet winding and its iron is very critical. A rotation of only 30° causes a normal sextupole to become "skew", not coupled at all to a "regular" field, and a rotation of 60° reverses the sign of the correction.

If mechanical alignment is to be used when the corrector is assembled into a new magnet, the assumption has to be made that the sextupole component of the dipole magnet's field is aligned with the dipole winding, which in turn must be aligned with the iron shield, the only external reference for such mechanical alignment.

Alignment Checks

Angular alignment can be rechecked after the magnet is in the cryostat, with the magnetic measurement coil array in place. The measurement is preferably done with the magnet superconducting and the cryostat full of liquid helium so that reasonable currents may be used. With the correction coil's heater on, to keep it quenched and passive, the field of the magnet is measured to find the magnitude and phase angle of the sextupole component at several currents. The magnet is then quenched to remove persistent currents, the correction coil heater is turned off, and the magnet is again run at the same currents, with magnetic field measurements as before. A vector subtraction for each current set yields the magnitude and direction of the sextupole field developed by the correction coil at that current. Table III gives some results for magnet D-12B(2) in terms of the Fourier-analyzed sextupole component magnitude and angle measured in "sextupole space".

Table III			
Magnet	Sextupole Coil Current	Sextupole Coil Self Powered	Sextupole Component Required to Produce Self Powered Result
300A	2009 @ 177.0°	207 @ -34.9°	2178 @ -5.9°
1000A	4456 @ 175.2°	317 @ -18.9°	4765 @ -5.8°
3000A	13907 @ 175.6°	775 @ -160.1°	13204 @ -5.8°

Since this is measured in sextupole space, the real angular misalignment, averaged, is -1.94° .

Alternatively, the correction coil quench heater is energized and the main magnet is run at a constant current. The coil is then externally powered at a series of currents and magnetic measurements are made. Magnitude and direction of the sextupole component are plotted for each

current. If an angular offset exists, a line through the vector tips will not pass through the origin, or 100% correction point. Instead, a "best" correction current will be obtained. Since the correction coil extends through the full length of the magnet, it will produce a weighted average correction field which may not fully correct either the central straight section or the ends of the magnet. The difference is magnified in these short magnets.

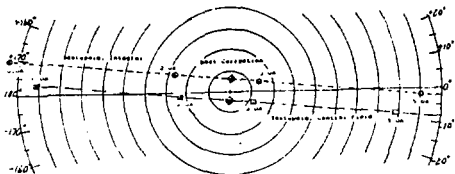


Fig. 2 Sextupole coil externally powered in magnet D-12B(2), showing the same angular offset arrived at in Table III above.

Conclusions

Local correction of dipole magnet field errors is both feasible and desirable. With carefully made multipole coils, properly proportioned and placed, chosen field harmonics can be reduced to below tolerance levels. These coils can be purely self-powered or provided with a quench heater and externally powered. In the latter case, auxiliary wiring is required as well as power supplies whose "tracking" currents will be difficult to arrive at and may require a cold field measurement of all the coils. The self-powered mode is quite adequate for this service and automatically adjusts to the error fields it couples, regardless of their origin.

The alignment problem can be handled by careful construction and mechanical alignment, or it could be handled automatically by having both a "regular" and "skew" winding on the same form. This arrangement would resolve the field vector and find the best adjustment to produce the required bucking field.

It is possible that beam induced quenches of the correction coils would permit error fields to reappear in a real accelerator ring in operation. It has been estimated that these coils could fail to operate properly in as many as 100 magnets in the SSC before some of the ring would need to be "reset", i.e., warmed up to about 10 K to quench the main and correction superconducting windings, removing all persistent currents.

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